Multi-isotope evidence for cattle droving at Roman Worcester

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Abstract

Tooth enamel from six cattle mandibles excavated from Roman deposits at The Hive development site, Worcester (mid-2nd to early 4th century AD) was subjected to strontium, oxygen and carbon isotope analyses ($^{87}Sr/^{86}Sr$, $\delta^{18}O$ and $\delta^{13}C$) to investigate the movement of cattle into Worcester, a purported regional cattle market, during the Roman period. Strontium isotope ratios show that none of the cattle were born and bred in close proximity to Worcester and arrived as mature beasts some time before death. Whilst two are consistent with origins in the region of Old Red Sandstone of Herefordshire to the west, the unusually high strontium isotope ratios of four of the cattle (i.e. >0.714) show that they originated in a region of ancient or radiogenic rocks such as granites which are found only in the west and north of Britain (e.g. Wales, the Lake District and northern Scotland) based on the currently available biosphere data. Comparison of the oxygen and carbon isotope values also suggests that the cattle were not from the same herd, but interpretation is complicated by the lack of comparative cattle data for the Roman period as well as other time periods. The severe wear of the molars from the aged cattle in this study also limits the interpretation of the results. More isotopic analyses are needed from other British sites in order to fully understand the implications of cattle movement into urban centres during the Roman period.

Keywords: Strontium; carbon; oxygen; isotope analysis; tooth enamel; intra-tooth sampling; cattle movement

1. Introduction

The primary aim of the study was to improve understanding of Roman cattle droving and the potential status of Roman Worcester as a cattle market by investigating the origins and movement of cattle to Worcester in the Roman period based on bone recovered from The Hive development site (specifically the mid-2nd to early 4th century AD). To achieve this, tooth enamel from six cattle mandibles was subjected to strontium, oxygen and carbon isotope analysis ($^{87}Sr/^{86}Sr$, $\delta^{18}O$ and $\delta^{13}C$). Strontium and oxygen isotope analysis have the potential to determine whether the cattle were of local or non-local origin, whereas carbon isotope analysis can inform on diet and the environment in which the cattle were living during tooth formation.

1.1 Archaeological context

1.1.1 Overview

Worcester (Figure 1), the county town of Worcestershire, UK, is mainly situated to the east of the River Severn. The core of the city sits on sand and gravel deposits of the Second (Worcester) Terrace and overlies the Mercia Mudstone geology formation, a series of sandstone, siltstones and mudstones of Triassic age (Dalwood and Currie 2004; Figure 2). Roman settlement at Worcester has long been recognised, with Roman finds recorded in the 17th, 18th and 19th centuries, but it was not until widespread redevelopment in the post-war period that the archaeological evidence began to be revealed with regularity.

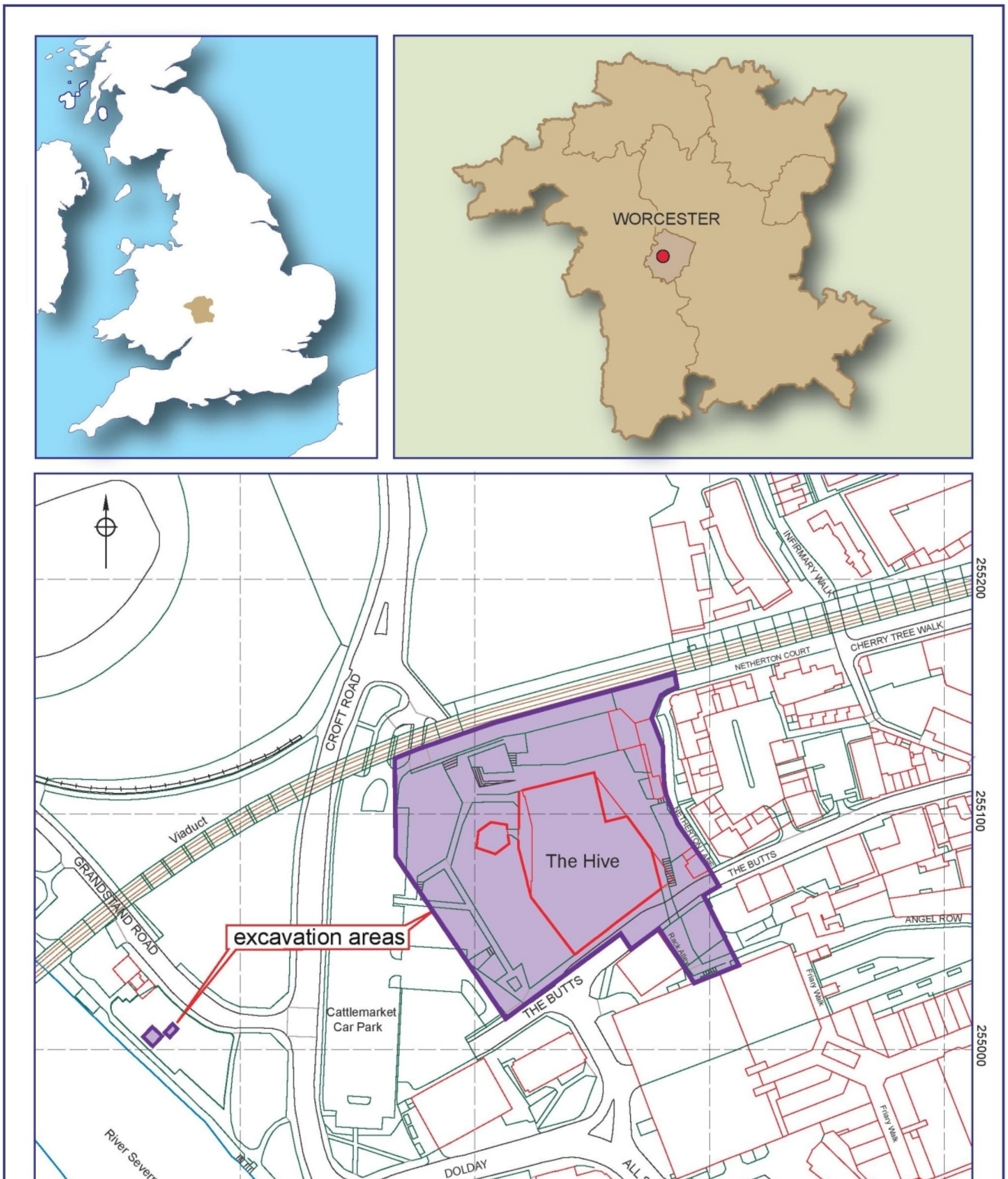

Figure 1. Location of Worcestershire within the UK (top left) with Worcester highlighted (top right). Ordnance Survey map showing the location of The Hive excavation areas in Worcester (bottom). Publishing licence has been obtained from Ordnance Survey to reproduce the map.

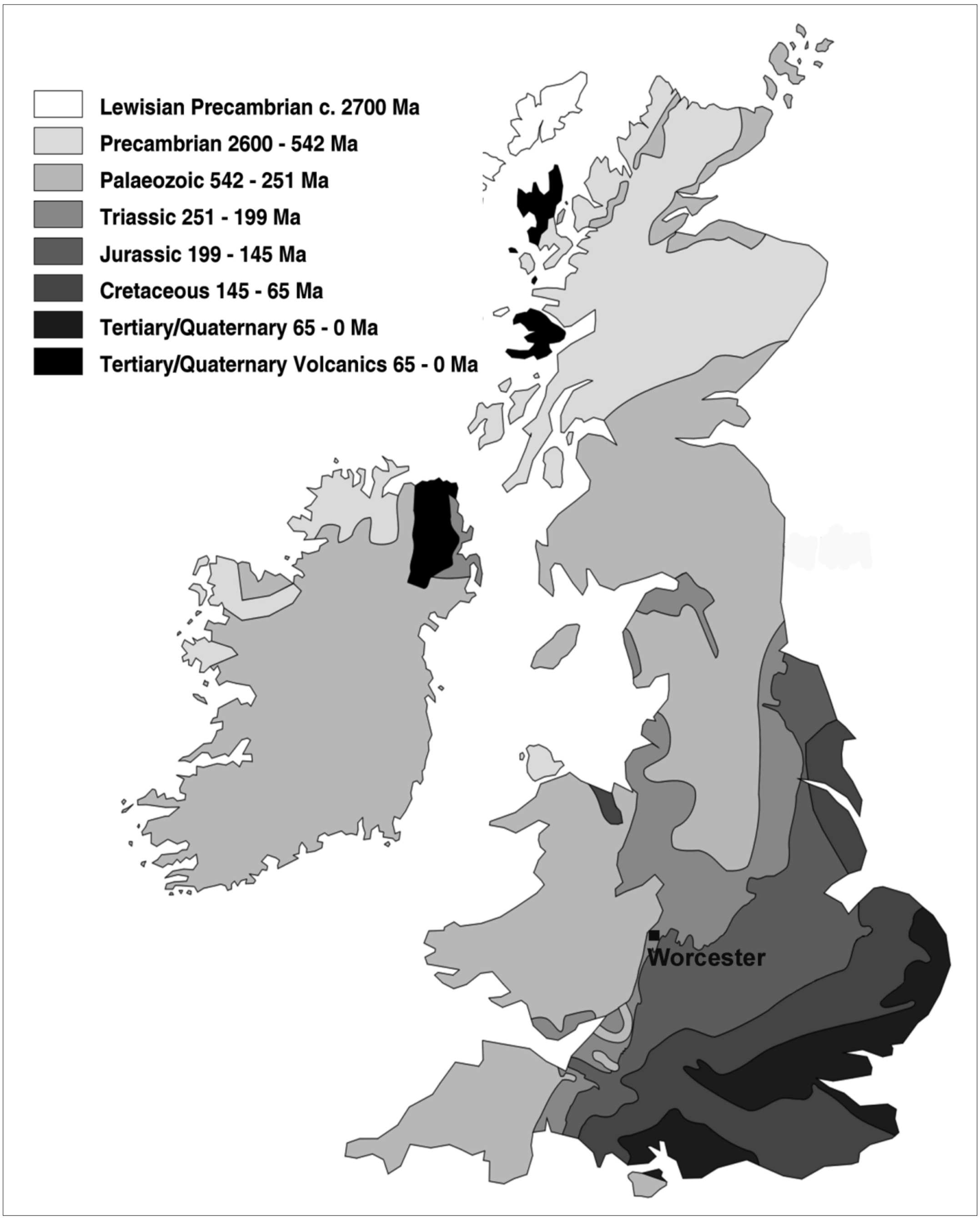

Figure 2. Simplified geological map of the United Kingdom showing the location of Worcester.

It is possible that the Roman 'small town' developed as an urbanisation of a pre-existing Iron Age centre of occupation, perhaps a defended enclosure; rescue excavations at Lich Street in the centre of the city identified a large ditch, which may have defined a settlement area, dated to the Iron Age (Barker 1969). Cunliffe (1991) has previously proposed that this may have taken the form of a political centre for the Dobunni tribe, though this hypothesis has not been revisited. Support for the Iron Age origins of the Roman town has more recently been revealed beneath the site of the Norman castle, close to the Cathedral, with the important discovery of a palisaded rampart scientifically dated to the 7^{th} to 5^{th} centuries BC (Napthan 2014).

Although the development process for the early Roman settlement remains unclear, an issue partly hindered by a lack of any structural evidence associated with the conquest, it has been argued that a fort was established at Worcester and occupied up to c. AD 75, mainly due to the strategic location at a crossing point of the River Severn in proximity to Wales, but also the occasional recovery of artefacts with military associations from sites on both the eastern and western side of the river (see Dalwood and Currie 2004; Dalwood 2004; Wainwright et al. 2014). Certainly, the town occupied a site with major regional trade links, with the river acting as an arterial transport route allowing the import of iron ore from the Forest of Dean and the export of regional produce such as salt from Droitwich and pottery from the Malvern area (Dalwood 2004). A number of roads also linked Roman Worcester with the regional economy: one went north and, although not fully traced, has been suggested to have led to Greensforge in Staffordshire; another, clearly linked to Droitwich, entered the settlement from the north-east; a third road to the south-east of the town is thought to have continued south to the legionary fortress at Gloucester (Dalwood and Currie 2004). A further Roman road running to the west has been suggested, but there is uncertainty about the crossing point over the River Severn (Dalwood and Edwards 2004).

Significant excavations that have helped to identify the extents and economy of Roman Worcester include those at Lich Street (Barker 1969), Sidbury (Darlington and Evans 1992), Deansway (Dalwood and Edwards 2004), 8-12 and 14-24 The Butts (Butler and Cuttler 2011), St. Martin's Gate, Lowesmoor (Butler and Cuttler 2011), and the University of Worcester City Campus (Sworn et al. 2014). These investigations have demonstrated that a fairly substantial civil settlement appears to have developed during the late 1st century AD, with an economy based on both agriculture and some ironworking, before more intensive land use during the 2nd century AD onwards, located on both the gravel terrace and river floodplain. Evidence for ironworking from the 2nd to mid-4th century AD is more widespread in the form of production areas for iron smelting, as well as smithing, and considerable waste dumps of iron slag, attesting to the scale of the industry. It has been suggested that this output may have been one component of a wider West Midlands 'resource-procurement zone', including Droitwich salt, Malvernian pottery, iron from Weston-under-Penyard (Herefordshire), and lead from Shelve (Shropshire), exploited to supply the army throughout the occupation of the province and falling under centralised official jurisdiction (see Esmonde-Cleary 2011). The stable isotope results presented here and the archaeological evidence from The Hive (Bradley et al. in press) and Deansway (Dalwood and Edwards 2004), as well as other sites in and around Worcester, would suggest that cattle were also an important traded resource in the region.

During the later 4th century AD, there appears to have been an uneven contraction of the settlement at Worcester, with continuity of occupation in some areas but a reversion to agriculture in others, and a cessation of the large-scale industrial production seen in previous centuries. This is consistent with wider patterns reflecting the fortunes of the Roman economy during the last quarter of the 4th century AD. At Sidbury in the south-east of the town, for example, occupation appears to have ceased c. AD 320, with a build-up of flood and waste deposits across a road surface (Darlington and Evans 1992). At City Campus, just north of The Hive, the absence of diagnostic later 4th century AD artefacts has suggested abandonment, and areas previously used for quarrying and agricultural buildings were subsequently sealed by a formation of late Roman agricultural tillage soil (Sworn et al. 2014). On the Deansway site, buildings formerly used for industrial purposes were replaced with animal pens and a small cemetery by the mid-4th century AD (Dalwood 2004).

1.1.2 The Hive site

Excavation at The Hive (Figure 1), the most recent large-scale investigation of Roman Worcester, covered an area of approximately 1.2 ha and produced one of the largest and most important groups of Roman features and artefacts from the settlement to date (Bradley et al. in press). Roman occupation was broadly consistent with surrounding excavations, being dated to the late 1st to late 4th century AD and most intensive between the mid- to late 2nd century and the early 4th century AD, when the settlement was at the height of its economic output but added many new insights into the character and development of the town.

Activity was recorded on the edge of the gravel terrace and the terrace slope, and down across the historic floodplain of the River Severn, where extensive dumping of iron slag demonstrated that large-scale and managed land reclamation was occurring. Slag along the riverside was used as a revetment or consolidation to create a stable area, probably for off-loading goods or foodstuffs at a jetty or quay, or perhaps as a firmer beaching area for vessels. Structural and occupation evidence was focused along the northern edge of the excavation where the gables of buildings abutted a road aligned east to west leading to the river frontage. The buildings are largely interpreted as commercial in function and perhaps represent a small-scale trading district that serviced riverside and roadside industrial working. In the earlier period of site occupation, the buildings were small and rectangular, built using clay and timber, with numerous internal ovens or hearths.

The site exhibited a brief period of abandonment, then a clear change in use during the mid-4th century AD. This was defined by disuse of the small buildings, clearance of middened waste into quarry pits, considerably less pottery than that of earlier dates, and the redevelopment of the area in a different format, based around a large aisled building and stone-built malting oven. These features were considered to be agricultural in use and it is possible that they were related to a suburban property associated with, or subsidiary to, an established town house or villa building nearby. High status building material has previously been recovered from this area of the settlement, and later Roman finds from The Hive consistent with this localised evidence included stone roof tile, box flue tiles, an antefix and slipped tegula. As part of this changing landscape, there were also indications that ‘dark earth’ and agricultural tillage soil was accumulating. Soil micromorphology and environmental evidence suggested that domestic animals were managed or grazed on waste ground and that the area may have become something of a late Roman suburban brownfield site.

1.1.3 Cattle in Roman Worcester

The possibility that Worcester acted as a cattle market and distribution centre during the Roman period is based on an idea postulated following the extensive Deansway excavations (Dalwood & Edwards 2004), reflecting evidence from both Worcester and surrounding rural sites.

At Deansway, cattle were predominant, a pattern that is common in Roman Worcester (e.g. Cuttler et al. 2011; Sworn et al. 2014), as well as at numerous sites elsewhere in Britain due to their broad multi-purpose use (Cheung et al. 2012; Dobney 2001; King 2001). Indeed, where a dominance of cattle is identified this has often indicated a characteristically Roman signature for settlements, reflecting the supply requirements of the Roman army in the agricultural and urban economy, and where they are less prevalent this has been thought to show that sites were subject to a more locally orientated economic output without centralised organisation (see Dobney 2001; King 1978, 1984, 2001; Nicholson and Scott 2004).

Alongside the animal bone, soil micromorphology of deep deposit accumulations in the excavated areas at Deansway suggested intensive animal penning in the 2nd to 4th centuries AD, probably in hedged paddocks. Post-built structures were also identified as animal sheds. The interpretation was that the movement and penning of stock was a significant part of the economy of the settlement (alongside ironworking), which in turn played a part in the wider provincial economy (Dalwood 2004), potentially where cattle from rich pasturelands in the west of the region or Wales were corralled and held prior to droving to towns and forts further east and north in the midlands and beyond. There is historical evidence for droving of cattle from Wales through England from at least Norman times, so it is possible that the historic record may reflect continuity of earlier practice (Featherstone 2003). Other sites suggested to have been involved in the movement of livestock to the north of Worcester, and perhaps linked to an associated regional distribution network, include Church Farm West, Grimley (5 km north; Webster and Jackson 2016), and Longdales Road, Kings Norton (38 km north-east; Jones et al. 2008). At Grimley, on the basis of limited occupation debris, a sequence of enclosures with associated tracks, droves and field boundaries were considered to have been seasonally used to corral stock, possibly on the way out of Worcester, before being moved on to market towns further afield. At Kings Norton, similar features with funnelled entrances were interpreted as representing a corralling and droving livestock management complex.

As with Deansway, the archaeozoological assemblage from The Hive was dominated by domestic mammals, with cattle being the most common species in the Roman period based on both number of identified specimens (NISP; 1782/2484 or 71.74%) and minimum number of individuals (MNI; 202/261 or 77%). The cattle found at The Hive belong to the small-horned and short-horned types and whilst juveniles and sub-adults were also represented, the majority were adult. Mandibles were dominated by adult and elderly beasts and most preserved epiphyses were fused, with pathologies associated with the use of cattle for draught purposes observed (Baxter in press). Of particular note, the morphology of the posterior cranium of the cattle was very variable, particularly in the later Roman period, suggesting a heterogeneous population consisting of unrelated stock derived from multiple localities. Additionally, congenital defects such as the presence or absence of occipital perforations and reduction or absence of the lower 3rd molar hypoconulid suggested that some of these cattle shared a genetic relationship (Baxter in press).

1.2 Cattle tooth enamel formation

Teeth consist of two main parts: the crown and the root(s). The crown is coated with a layer of enamel, which is unique among biological tissues in that in its mature form it is mostly inorganic (c. 96%) and contains less than 1% organic material (percentages by weight) (Hillson 2005). The inorganic fraction of enamel is a carbonated hydroxyapatite (also referred to as apatite or bioapatite in the literature) consisting of calcium (Ca^{2+}), phosphate (PO_4^{2-}) and hydroxyl (OH^-) ions but with several common ionic substitutions such as strontium (Sr^{2+}) and carbonate (CO_3^{2-}) which are the source of the isotopes measured in this study. Due to the acellular, avascular, dense and highly crystalline structure of enamel, it is often very well preserved in the archaeological record and largely retains its biological integrity (Montgomery et al. 2010). Because enamel does not remodel once it is fully mineralised, it records the isotopic composition of the animal's diet and environment during the period of mineralisation (Balasse 2002; Passey and Cerling 2002; Zazzo et al. 2005). It is thus considered a suitable material for strontium, oxygen and carbon isotope analysis and is widely used in archaeological research.

	First molar (months)	Second molar (months)	Third molar (months)
Start of crown formation	In utero	1	9-10
Completion of crown formation	2-3	12-13	23-24

Table 1. Chronology of development for mandibular cattle molars (Brown et al. 1960). Timings relate to enamel matrix progression.

Tooth enamel formation, known as amelogenesis, consists of two main stages – the initial enamel matrix formation stage and the later enamel maturation stage (Brown et al. 1960; Hillson 2005). The organic matrix becomes lightly mineralised, as it is secreted ahead of maturation. For cattle, in terms of matrix progression, permanent molar crown formation starts in utero and continues through approximately the first two years of life (Table 1). Each molar forms sequentially from the occlusal cusp (tip) to the cervix (neck), suggesting the possibility of an isotopic timeline recorded within the enamel. However, enamel maturation is complex, and, in the case of cattle enamel, the process can take more than 6-7 months at any one location on the tooth (Balasse 2002) with waves of mineralisation occurring in various directions (Zazzo et al. 2006). This impacts on the temporal chronology of recovered signals, as although the enamel matrix and initial mineralisation starts at c. 1 month in second molars, the occlusal enamel will not complete maturation until c. 7-8 months. Consequently, measured isotope values are not discrete chronological archives of specific inputs but rather weighted continuous averages which depend on relative contributions and changing isotope ratio inputs (Montgomery et al. 2010; Passey and Cerling 2002; Zazzo et al. 2005; Zazzo et al. 2012). Establishing precisely when during the period of maturation an isotope value derives from can therefore be difficult to ascertain with certainty.

2. Isotopic analysis

2.1 Strontium ($^{87}Sr/^{86}Sr$) isotope analysis

Unlike carbon and oxygen which are reported relative to a defined and accepted standard, strontium isotopes are reported simply as the measured ratio of ^{87}Sr to ^{86}Sr ($^{87}Sr/^{86}Sr$). A more comprehensive account of the strontium isotope system is provided elsewhere (e.g. Bentley 2006; Montgomery 2010) but in short, ^{87}Rb that is naturally occurring in rocks undergoes radioactive decay over geological timescales to form ^{87}Sr. Therefore, $^{87}Sr/^{86}Sr$ is essentially a function of the relative abundances of rubidium and strontium at formation and the age of the rocks as ^{87}Sr increases over geological time. Strontium enters the soil through the 'weathering' process of minerals, and subsequently enters plants and proceeds up the food chain. This produces geographical variation in the $^{87}Sr/^{86}Sr$ released from rocks in soils and subsequently into plants along with atmospheric inputs from rain or dust, i.e. the biosphere ratios. Consequently, old or granitic rocks can host Sr-isotope biospheres with plant $^{87}Sr/^{86}Sr$ ratios of >0.716, whereas rocks such as volcanic basalts have $^{87}Sr/^{86}Sr$ biosphere plant ratios of <0.707 (Evans et al. 2010).

Strontium in cattle molar enamel is primarily ingested from vegetation and, to a lesser degree due to its low concentration of strontium, drinking water. If food is sourced locally rather than imported from elsewhere, the $^{87}Sr/^{86}Sr$ ratios measured are determined predominantly by the underlying geology, solid or drift, of the region in which the animal was sourcing food at the time of tooth formation and atmospheric deposition in the form of dust, and more commonly in maritime islands such as Britain, rainfall (Bentley 2006; Montgomery 2010).

2.2 Oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotope analysis

Diverse physical properties cause isotopes to behave differently in physical processes such as evaporation, condensation and diffusion. This phenomenon is known as isotope fractionation (Schoeller 1999), and it affects the relative abundances of stable light isotopes such as those of oxygen and carbon.

Stable isotopes, are commonly reported using the delta (δ) notation in parts per thousand (or per mil, ‰). The value of δ is given by (Coplen 2011)

$$\delta = \left(\frac{R_{sample}}{R_{standard}}\right) - 1$$

The δ value compares the ratio of the heavy isotope abundance to the light isotope abundance in the sample (R_{sample}) to that of the standard ($R_{standard}$). Therefore, a positive δ value indicates that there are more heavy isotopes in the sample than there are in the standard, and vice versa for a negative δ value. $\delta^{18}O$ values are reported relative to the Vienna standard mean ocean water (VSMOW) international reference standard. $\delta^{13}C$ values are reported relative to the Vienna Peedee belemnite (VPDB) international reference standard.

Oxygen in cattle molar enamel is ingested primarily from drinking water the source of which, whether ground or surface water, is typically local rainwater (Longinelli 1984). The $\delta^{18}O$ values are thus ultimately controlled by the topographical and climatic factors (e.g. altitude, latitude, temperature etc.) of the region in which the rain falls (Daansgaard 1964). Generally, summer (high temperature) and low altitudes are indicated by high $\delta^{18}O$ values and vice versa (Darling and Talbot 2003). This is because as condensation temperature decreases, the heavier ^{18}O isotope content in precipitation decreases, resulting in lower $\delta^{18}O$ values in drinking water (Daansgaard 1964; Sharp 2007). In Britain, a region with a higher $\delta^{18}O$ value is also usually a region with a higher annual rainfall (Evans et al. 2010) as a result of prevailing southwesterly winds and rainclouds; therefore, the ^{18}O content of rainwater becomes more depleted due to processes such as evaporation and condensation as the rainbearing clouds move eastwards. In spite of the fact that cattle are obligate drinkers and their $\delta^{18}O$ values should strongly reflect the local rainwater values, husbandry practices, such as seasonal movement up to the mountains during the summer, could suppress the natural extremes of summer and winter in the output signal of the cattle's isotopic profiles (Balasse 2003).

Oxygen isotope analysis of tooth enamel can be conducted on the phosphate or carbonate fraction. For this study, carbonate is selected for analysis, as both the carbon and oxygen isotopes can be measured concurrently (Sponheimer and Lee-Thorp 1999). Moreover, the sample preparation process is considerably less laborious to produce a higher number of measurements (Pellegrini et al. 2011). Although there has been considerable debate in the literature regarding the suitability of carbonate for conducting oxygen isotope analysis, studies (e.g. Cerling et al. 1997; Chenery et al. 2012; Sponheimer and Lee-Thorp 1999) have shown that enamel carbonate can produce valid and robust results and the oxygen isotope values of carbonate and phosphate in enamel apatite are highly correlated (Bryant et al. 1996; Chenery et al. 2012).

Carbon is incorporated into an individual via the consumption of foodstuffs and the $\delta^{13}C$ values of enamel carbonate derive from blood bicarbonate reflect the whole diet of the animal (Sealy 2001). For cattle, the diet is usually composed of vegetation, the $\delta^{13}C$ value of which is influenced by species (C_3 vs. C_4 plants), plant part and the growing environment (Heaton 1999; Tieszen 1991). Factors affecting the growing environment and, hence, the $\delta^{13}C$ value of vegetation include water availability, salinity, irradiance, altitude, seasonality and the "canopy effect" whereby vegetation growing at ground level within dense tree cover tends to exhibit lower $\delta^{13}C$ values than vegetation growing in more open environments (Dungait et al. 2010; Heaton 1999; Tieszen 1991). Therefore, it may be possible to detect a difference in the $\delta^{13}C$ values of cattle subjected to a different climate or husbandry practices (e.g. Millard et al. 2013). As very few C_4 plants are indigenous to Britain they make a negligible contribution to animal and human diets throughout prehistory. However, C_4 plant consumption has been observed in a small number of human individuals of Roman date in southern Britain but in each case, they were identified as immigrants from mainland Europe who had been consuming C_4 foods prior to arrival in Britain (Müldner 2013). As there is currently no evidence for the consumption of C_4 fodder by domestic animals in Britain at this time, only information related to C_3 plants is considered relevant to this study. In general, the $\delta^{13}C$ values of modern C_3 plants worldwide range from -31‰ to -23‰, with a mean value of -27‰ (Kohn 2010). Perhaps of more relevance here are the results from a study of herbs and grasses from cattle-grazed meadowland in Somerset, UK, which produced $\delta^{13}C$ values in the range of -31.1‰ to -26.9‰ and a mean value of -28.7‰ (Dungait et al. 2010). Applying a correction of +2.0‰ to account for the fossil fuel effect (Friedli et al. 1986; Keeling et al. 2010), equivalent pre-industrial values would be -29.1‰ to -24.9‰ (range) and -26.7‰ (mean). For domestic cattle, an isotopic enrichment (ε^*) between tooth enamel and dietary $\delta^{13}C$ values has been measured at 14-16‰ (Passey et al. 2005; Towers 2013). Offsets for ruminants such as cattle tend to be higher than for non-ruminants consuming the same diet because fermentation in the rumen produces ^{13}C -enriched carbon dioxide (CO_2), a proportion of which becomes incorporated into enamel (Passey et al. 2005). Applying the range of enamel-diet enrichment values to the pre-industrial range of C_3 vegetation values calculated above suggests that enamel $\delta^{13}C$

values for pre-industrial British cattle might be expected to fall between around -15 and -9‰.

3. Materials and methods

3.1 Sampling method

The cattle were selected by means of ageable mandibles to ensure that they were different individuals (HEAS 2011). All of the mandibles, designated WCM 1-6, were from Period 5 in the site stratigraphic sequence (early/mid-3rd – early 4th century AD), with the exception of one mandible from Period 4 (mid-2nd – early 3rd century AD) (Table 2).

Mandible ID	Context no.	Context type and description	Context group (CG)	Site period
WCM 1	6474	Fill – Dark greyish brown silty clay	1087 – Pit cutting cobbled surface 1045	5
WCM 2	6519	Layer – Not excavated	1048 – Deposits below cobbled surface 1045	4
WCM 3	6753	Layer – Blackish grey silty loam	1041 – Deposits below cobbled surface 1045	5
WCM 4	6588	Fill – Mid-brown grey sandy silt	1086 – Smaller features cutting cobbled surface 1045	5
WCM 5	6516	Layer – Mid-grey brown sandy silt	1047 – Demolition / levelling above cobbled surface 1045	5
WCM 6	6516	Layer – Mid-grey brown sandy silt	1047 – Demolition / levelling above cobbled surface 1045	5

Table 2. Context information for each cattle mandible analysed in this study. Site period 4 = Roman (mid-2nd to early 3rd century AD); site period 5 = Roman (early/mid-3rd to early 4th century AD).

For the strontium isotope analysis, a sample was taken from the first, second and third molars of each animal. For each molar, a single sample of enamel weighing approximately 20 mg was collected from a position close to the occlusal surface using a diamond-tipped rotary dental saw (Figure 3). However, as most of the teeth were very worn, the majority of samples originated from the cervical area of the molars (Table S1). Each sample was extracted by cutting through the whole thickness of enamel. The dimension parallel to the direction of tooth growth (~1-2 mm) represents <1 month of tooth growth in terms of matrix progression but would have taken at least 6-7 months to mineralise (Balasse 2002). Moreover, the time period represented by the enamel sample may be longer than this because strontium ingested before the commencement of enamel mineralisation and incorporated into bone bioapatite may have been recycled and subsequently incorporated into the enamel (Montgomery et al. 2010). Thus, an estimation of the time span in the lives of the cattle represented by these samples is difficult. However, samples from first, second and third molars can be analysed to provide diachronic information on residence during the first c. 30 months of life.

Figure 3. Enamel sampling of the third molar of WCM 5. Ten intra-tooth powdered samples were obtained from the lingual surface of mesial lobe for $\delta^{18}O$ and $\delta^{13}C$ analyses, while a single chip of enamel was obtained from the lingual surface of mesial lobe for $^{87}Sr/^{86}Sr$ analysis.

For the $\delta^{18}O$ and $\delta^{13}C$ analyses, sequential enamel samples were collected from the lingual side of second and third molars to produce isotopic profiles over the period represented by each tooth. Using a diamond-tipped burr, the cementum was removed, and the enamel surface cleaned before intra-tooth samples of powdered enamel were obtained by drilling through the bulk of the enamel thickness in order to produce a series of sequential samples perpendicular to the tooth growth axis (Figure 3). Sequential sampling was carried out on three cattle (WCM 1, WCM 3 and WCM 5), but only a single sample was obtained from cattle WCM 2, WCM 4 and WCM 6, as these teeth were extremely worn. Approximately 15 mg of powdered enamel were obtained for each sample to provide sufficient material for repeat analyses if needed.

3.2 Sample preparation

3.2.1 Strontium isotope analysis

The enamel samples were prepared following the procedure given in Montgomery (2002). All surfaces of the enamel samples were cleaned and polished with a diamond-tipped dental burr to a depth of >100 µm to remove traces of contaminants such as soil and dentine. The cleaned samples were analysed in the Northern Centre for Isotopic and Elemental Tracing (NCIEP) at the Department of Earth Sciences, Durham University using column chemistry methods outlined in Charlier et al. (2006). They were heated on a hot plate for 20 minutes in 75 µl of 16N HNO_3. The solution was then diluted with 325 µl of MQ H_2O and heated overnight. The samples were loaded into cleansed and preconditioned columns containing 60 µl of strontium-specific resin. 2x250 µl 3N HNO_3 was passed through to elute the waste, then 2x200 µl MQ H_2O was passed through to elute the strontium, which was collected.

Following preparation, the size of the ^{86}Sr beam was tested for each sample to assess the strontium concentrations. From this analysis, a dilution factor could be calculated for each sample and each was diluted to yield a beam size of approximately 20 V ^{88}Sr, where possible, to match the beam size of the isotopic reference material, NBS987.

The strontium samples were taken up in 1 ml of 3% HNO_3 and were analysed by Multi-Collector Inductively Coupled Plasma Mass Spectrometry (MC-ICP-MS) using a Neptune MC-ICP-MS. Samples were introduced into this using an ESI PFA50 nebuliser and a glass expansion cinnabar micro-cyclonic spray chamber.

Instrumental mass bias was corrected for using an $^{88}Sr/^{86}Sr$ ratio of 8.375209 (the reciprocal of the $^{86}Sr/^{88}Sr$ ratio of 0.1194 and an exponential law. Corrections were also applied for Kr interferences on ^{84}Sr and ^{86}Sr and the Rb interference on ^{87}Sr by monitoring masses ^{82}Kr, ^{83}Kr and ^{85}Rb. The average ^{83}Kr intensity throughout the analytical session was ~0.06 mV, which is insignificant considering the Sr beam size (^{88}Sr between 11 and 21 V). The average ^{85}Rb intensity was slightly greater at ~0.3 mV (range: 0.04-5.47 mV) but again, given the range in Sr beam size, the Rb correction on the $^{87}Sr/^{86}Sr$, even for the sample with ~5 mV of Rb, was very small (<0.00001) and is accurate at that magnitude.

The samples were analysed in a single analytical session during which the average $^{87}Sr/^{86}Sr$ value and reproducibility for NBS987 was 0.710269±0.000015 (2σ; n=12). Data in Supplementary Table S1 are renormalised to an accepted value for NBS 987 of 0.71024.

3.2.2 Oxygen and carbon isotope analysis

The enamel samples were treated and analysed in the Stable Light Isotope Facility at the University of Bradford following the procedure given in Towers et al. (2014). The enamel powder was subjected to a pre-treatment process modified after Sponheimer (1999). 1.8 ml of 1.7% sodium hypochlorite (NaOCl) solution was first added and left for 30 minutes to remove any organic matter. The samples were then rinsed with distilled water and centrifuged at least 3 times to ensure that all NaOCl solution was removed. 1.8 ml of 0.1 M acetic acid (CH_3COOH) was added for not more than 10 minutes and centrifuged once prior to the end of the 10-minute period to remove any exogenous carbonate. The samples were rinsed again with distilled water and centrifuged at least 3 times to ensure that all acetic acid was removed. The samples were then freeze-dried.

~2.5 mg of the treated samples was then weighed and loaded into the Finnigan Gasbench II, which is connected directly to the Thermo Delta V Advantage continuous flow mass spectrometer. The enamel carbonate of each sample reacted with anhydrous phosphoric acid (H_3PO_4) at 70°C for approximately 1 hour, resulting in the release of CO_2, which was analysed by the mass spectrometer along with the CO_2 from a reference supply. The obtained $\delta^{18}O_{VSMOW}$ and $\delta^{13}C_{VPDB}$ values were normalised relative to the measured and approved lab and international standards (NBS19, Merck Supra-pure calcium carbonate, CO-1 marble, and CO-8 calcite). Analytical precision was ±0.2‰ (1σ) for both $\delta^{18}O_{VSMOW}$ and $\delta^{13}C_{VPDB}$.

4. Results

4.1 Strontium isotope analysis

The strontium isotope results are presented in Supplementary Table S1 and Figure 4. The three values for each animal reflect residence and mobility from the first months of life up to c. 30 months of age. Some cattle show limited variation over this period of time, e.g. WCM 1, WCM 2 and WCM 4, whilst others have substantial changes, e.g. WCM 3 and WCM 6. All $^{87}Sr/^{86}Sr$ values, which range between 0.71211 and 0.71582, are significantly higher than the upper limit expected for the biosphere hosted by the Triassic rocks (mudstone, siltstones and sandstone) and Quaternary alluvium and river terrace deposits upon which Worcester sits (Figure 4). Such Triassic rocks crop out extensively across central England and extend in all directions from Worcester itself. The $^{87}Sr/^{86}Sr$ range of the biosphere hosted by such rocks was reported by Evans et al. (2010, supplementary appendix) to be 0.7097±0.0006 (1σ, n=54, supplementary appendix) with no values higher than 0.7116, and includes aquifer water data from Spiro et al. (2001) and Montgomery et al. (2006) who demonstrated a correlation between mineral waters and the geological age or lithology of the host rock. This range is supported by human isotope data from the broadly contemporary Roman and early medieval site of Wasperton, c. 40 km to the east where the local $^{87}Sr/^{86}Sr$ range for people did not exceed 0.7107 (Montgomery et al. 2009).

Such ratios are entirely inconsistent with regions of basalts and limestones, including chalk (<0.710); the latter two occur widely across southern, central and eastern England (Evans et al. 2010). The cattle values are also higher and thus inconsistent with the Carboniferous (Coal Measures, Millstone Grit and limestones) regions to the north and the Jurassic and Cretaceous rocks to the south and east and any drift such as peat, marine sands and glacial deposits such as till, gravels and boulder clay (Evans et al. 2010). Consequently, it is highly unlikely that any of the cattle were raised or grazed in the vicinity of Worcester during the first c. 30 months life and origins for the cattle cannot be found to the south or east. Two cattle, WCM 4 and WCM 6, have $^{87}Sr/^{86}Sr$ values ranging between 0.712-0.714 and such values are typical of humans living in the large region of Devonian Old Red Sandstone in Herefordshire to the west of Worcester (Evans et al. 2010; 2012). The remaining four cattle have values above 0.714 which are highly unusual for southern Britain, although a study by Chenery et al. (2010) has shown that several modern plants from a geographically restricted area near the Malvern Hills have produced such high Sr values, and are indicative of ancient or granitic terrains (Evans et al. 2010).

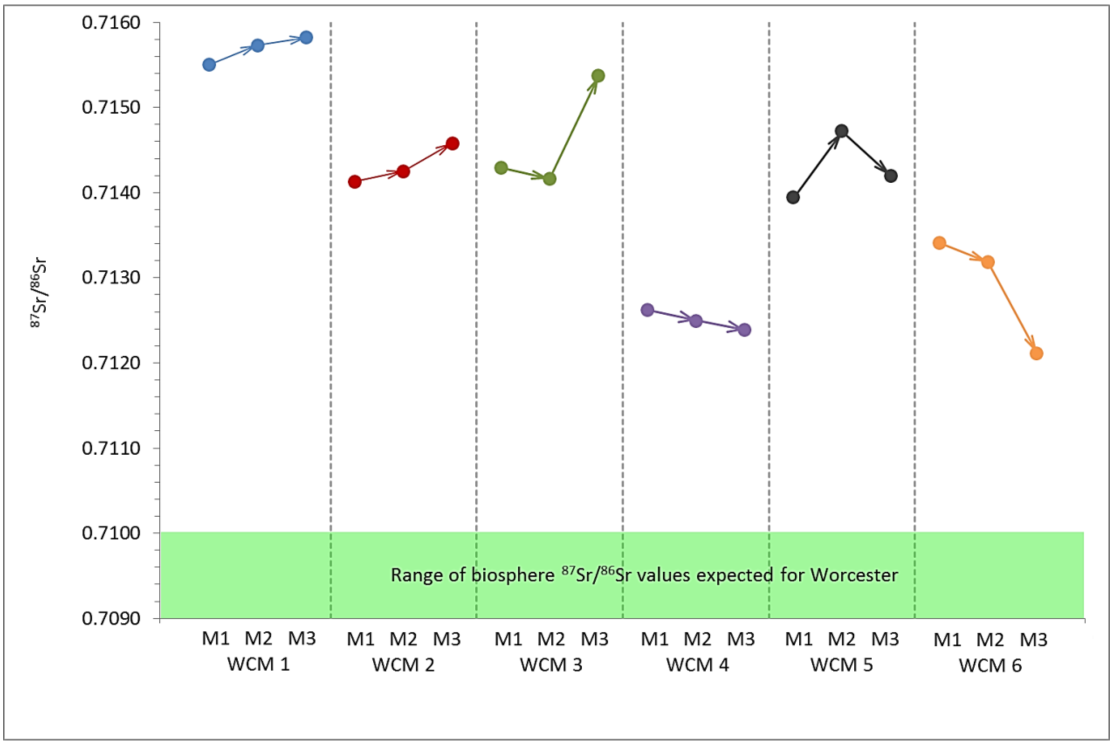

Figure 4. $^{87}Sr/^{86}Sr$ values for the Worcester cattle. The 2σ error is contained within the symbols. The range of biosphere $^{87}Sr/^{86}Sr$ values expected for Worcester and its environs is that given by Evans et al. (2010) for areas of Triassic geology and Quaternary alluvium and river terrace deposits. Arrows show the sequence of molar formation and hence how the $^{87}Sr/^{86}Sr$ values change from the first months of life up to c. 30 months of age.

4.2 Oxygen and carbon isotope analysis

The $\delta^{18}O$ values range from 22.1‰ to 26.0‰ and the $\delta^{13}C$ values range from -13.3‰ to -11.6‰ (Table 3). The $\delta^{18}O$ and $\delta^{13}C$ values for all cattle samples are provided in Supplementary Table S2. The ranges of the $\delta^{18}O$ and $\delta^{13}C$ values are generally consistent with published values for British cattle enamel carbonate (*cf.* Towers et al. 2011; Towers et al. 2014). The $\delta^{13}C$ values indicate the expected C_3 plant-based diet. Such $\delta^{18}O$ and $\delta^{13}C$ values however are not unique to Britain and comparable values are likely to be found across large parts of Europe subject to similar climatic and environmental conditions.

	Minimum value	Maximum value	Median
$\delta^{18}O_{VSMOW}$ (‰)	22.1	26.0	24.1
$\delta^{13}C_{VPDB}$ (‰)	-13.3	-11.6	-12.5

Table 3. Minimum values, maximum values and medians of $\delta^{18}O$ and $\delta^{13}C$ values for the enamel carbonate samples. A total of 41 carbonate samples have been obtained across the 6 cattle individuals in this study (refer Table S2 for full list of sample number for each individual).

Figures 5 and 6 respectively show the combined $\delta^{18}O$ and $\delta^{13}C$ profiles of all individuals. The isotope values (*y*-axis) are plotted against distance from the cervix (x-axis). Because of the chronology of cattle molar formation (Table 1), the x-axis represents a time-line and represents approximately the first 2.5 years of an animal's life with respect to enamel matrix progression. Each isotope value represents ~6-7 months of mineralization (Balasse 2002) subsequent to the initial matrix deposition at that position on the crown, i.e. up to a maximum age of c. 30 months.

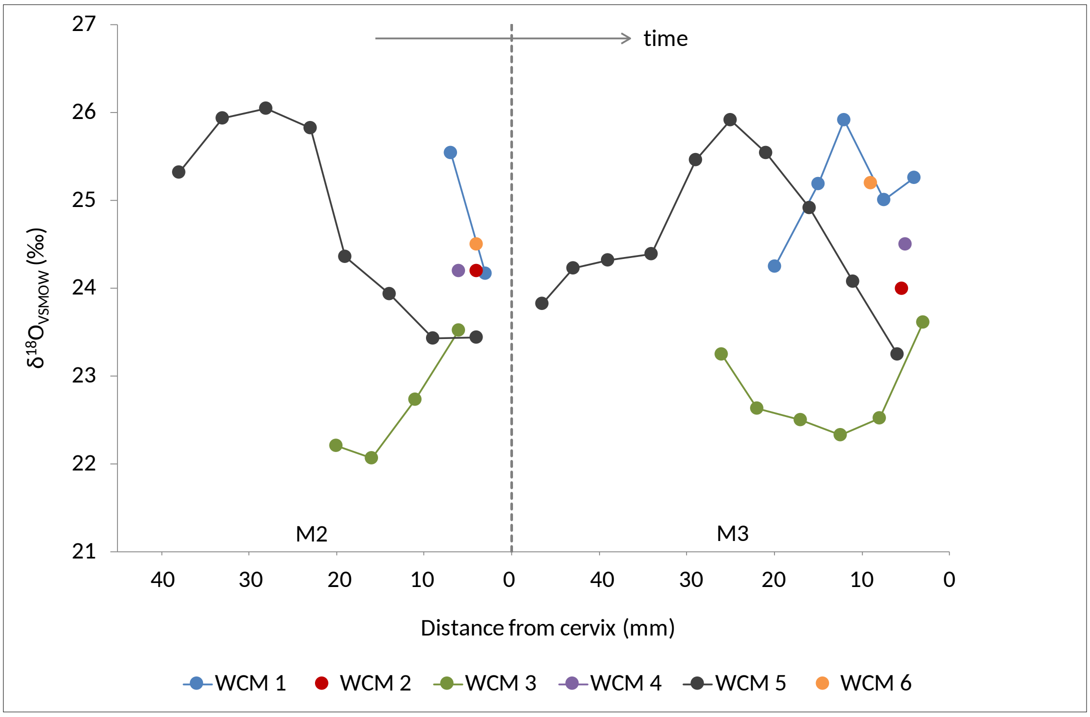

Figure 5. Intra-tooth $\delta^{18}O$ values for the Worcester cattle. Analytical precision was ±0.2‰ (1σ).

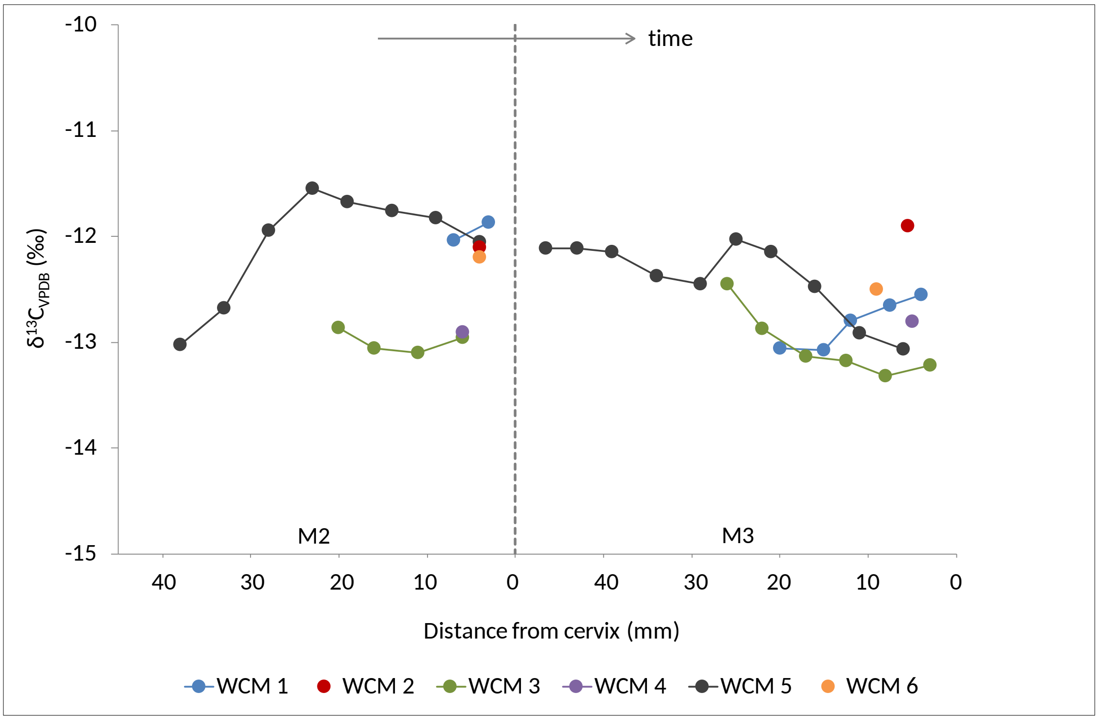

Figure 6. Intra-tooth $\delta^{13}C$ values for the Worcester cattle. Analytical precision was ±0.2‰ (1σ).

5. Discussion

5.1 Strontium isotope analysis

The $^{87}Sr/^{86}Sr$ values obtained from this study largely rule out most of southern Britain to the north, east and south of Worcester as potential places of origin for the cattle (Evans et al. 2010). The data demonstrates that all six cattle have been brought to Worcester from elsewhere at some time between the age of c. 30 months and death. Moreover, the range of values in the six cattle greatly exceeds the 0.00062 range observed in a single modern herd of grazing cattle (Towers et al. 2017) and suggests diverse places of birth. Three animals (WCM 1, WCM 2 and WCM 4) do not appear to have moved during the first c. 2.5 years of life as they exhibit only a small change in $^{87}Sr/^{86}Sr$ values between their three molar teeth. However, it is also possible that they moved between locations characterised by the same geological substrate. The remaining three animals have a larger shift in values which may indicate movement between different geological terrains, although different geological terrains could, in regions of heterogeneous ancient geology such as Wales, be as short a distance as to an adjacent field.

$^{87}Sr/^{86}Sr$ values for two of the six cattle (WCM 4 and WCM 6) are approximately 0.712-0.714, suggesting possible origins in Herefordshire, south Wales, the southwest of England, the Lake District and Scotland. Such values are highly characteristic of humans and animals originating in regions of Palaeozoic Devonian Old Red Sandstone, which provides the surface rocks across the aforementioned regions (Figure 2), but is largely absent from the rest of England (Evans et al. 2010). Several non-local cattle with these values were also found in the Roman period at Owlesbury in Hampshire (Minniti et al. 2014) and were deemed by the authors to be evidence for increasing trade and a widening market compared to the preceding Iron Age period.

The remaining four cattle show high $^{87}Sr/^{86}Sr$ values for Britain (>0.714), which are usually attributed to granitic or ancient (Proterozoic and Archaean) biospheres. In Britain, these are predominantly located in the upland areas of the west and north. Although values above 0.714 have been found in cattle from southern England previously, they are extremely rare (Table 4; Madgwick et al. 2017; Minniti et al. 2014; Viner et al. 2010). These four cattle from Worcester are, therefore, highly unusual in that all are non-local, and all have high to very-high $^{87}Sr/^{86}Sr$ values. This could be due to Worcester's proximity to Wales, which is a region of old, mountainous and complex geology. To date, comparable biosphere values from Britain have largely been found in areas of Scotland, e.g. Aberdeenshire and the Isle of Skye. No consistent evidence has yet been found that granitic or ancient geological areas of England can produce vegetation that could provide such high values in animals or humans although there are a few as yet uncharacterised but geographically restricted areas of granitic rocks, e.g. the Malverns, Dartmoor and the Lake District that have the potential to do so. However, on account of the steep topography, some may have been an unlikely location for cattle rearing. It is possible that the cattle originated to the west in Wales and were driven into Worcester: high $^{87}Sr/^{86}Sr$ values have been found at Penywyrlod and Ty Isaf monuments in south-east Wales where a small number of early Neolithic humans had values in the range of 0.714 to 0.717 although the authors could find no evidence that values above 0.716 could be provided from the Malverns or elsewhere in Wales (Neil et al. 2017). Whilst Wales may provide the nearest and archaeologically most feasible place of origin there are of course regions overseas such as Ireland and elsewhere in the Roman Empire, e.g.

Brittany, Spain, Portugal and southern France that would also be consistent with such high $^{87}Sr/^{86}Sr$ values.

Location	Period	No. of cattle studied	$^{87}Sr/^{86}Sr$ range of cattle enamel	No. 0.712 – 0.714	No. >0.714	Source
Durrington Walls, Wiltshire	Neolithic	13	0.7086 – 0.7148	2	1	Viner et al. 2010
Gayhurst, Buckinghamshire	Early Bronze Age	7	0.7085 – 0.7130	1	0	Towers et al. 2010
Irthlingborough, Northamptonshire	Early Bronze Age	9	0.7088 – 0.7117	0	0	Towers et al. 2010
Owlesbury, Hampshire	Mid-Iron Age	11	0.7088 – 0.7101	0	0	Minniti et al. 2014
Owlesbury, Hampshire	Late Iron Age	22	0.7081 – 0.7111	0	0	Minniti et al. 2014
Owlesbury, Hampshire	Early Roman	45	0.7079 – 0.7145	4	1	Minniti et al. 2014
Owlesbury, Hampshire	Mid-Roman	17	0.7080 – 0.7127	1	0	Minniti et al. 2014
Caerleon, Newport, Wales	Roman and post-Roman	16	0.7082 – 0.7151	3	1	Madgwick et al. 2017
Grimes Graves, Norfolk	Mid-Late Bronze Age	10	0.7084 – 0.7124	1	0	Towers et al. 2017

Table 4. Published cattle enamel $^{87}Sr/^{86}Sr$ values.

Variation in the $^{87}Sr/^{86}Sr$ values between different molars, particularly for WCM 3, WCM 5 and WCM 6 (Figure 4), suggests movement between different geological terrains during early life. Based on the $^{87}Sr/^{86}Sr$ values, none of the animals appear to have moved to the vicinity of Worcester during the period of molar formation except for possibly WCM 5 and WCM 6. The third molar cervical enamel of WCM 5 had not completely mineralised at death, which is highly likely to have taken place in Worcester. It was probably killed soon after arrival in Worcester since the Worcester biosphere $^{87}Sr/^{86}Sr$ values is not reflected in the enamel. As for WCM 6, the $^{87}Sr/^{86}Sr$ value of the third molar dropped considerably; it is possible that this value could be an average produced from earlier life residence and Worcester if the animal moved whilst the tooth was still mineralising.

5.2 Oxygen isotope analysis

The intra-tooth profile for WCM 5 clearly shows a sinusoidal variation with time. This reflects the seasonal variation of precipitation $\delta^{18}O$ values, which tend to be higher in summer and lower in winter at mid- to high latitudes (Daansgaard 1964). However, the natural environmental signal for a year might be attenuated by the enamel mineralisation process, a change in climate in that year, transhumance, or animal physiology and/or behaviour (Passey and Cerling 2004). The maximum and minimum points cover an intra-variability range of more than 2‰, which is typical of a seasonal range in the UK (Darling and Talbot 2003) and is also indicative of free-ranging cattle (Fricke et al. 1998). Free-ranging cattle tend to display a large intra-tooth $\delta^{18}O$ variation as opposed to non-free-ranging cattle that are fed with dry food and domestic water supply as these food sources rarely exhibit any $\delta^{18}O$ variation (*ibid.*)

A sinusoidal pattern is partially observable for WCM 3. Minimum $\delta^{18}O$ values for this animal are lower than for WCM 5, which may indicate a different birthplace, perhaps at a higher altitude although with comparable strontium isotope ratios. $\delta^{18}O$ values of precipitation decrease with altitude (Daansgaard 1964). In addition, in the British Isles, the values of $\delta^{18}O$ for groundwaters, which preserve long-term average rainfall values, tend to decrease from west to east (Darling and Talbot 2003). In the absence of comparative local cattle, it is not possible to say if these values are also consistent with the Worcester region.

5.3 Carbon isotope analysis

Although the $\delta^{13}C$ values are indicative of a C_3 plant-based diet, the $\delta^{13}C$ variation in Figure 6 does not show a sinusoidal pattern, unlike the $\delta^{18}O$ profiles. For WCM 3 and WCM 5, the peaks and troughs for the $\delta^{13}C$ variations are generally simultaneous with their respective $\delta^{18}O$ variations. This could indicate that the cattle were grazing in the same type of environment throughout the year as micro-scale climatic fluctuations can have effects on vegetation (Wiedemann et al. 1999) that are comparable to the climatic effects on drinking water. It is also possible that the $\delta^{13}C$ variation is a result of seasonal variation in plant species (Tieszen 1991) or plant parts fed to the cattle as it is known that different plant species and/or plant parts produce variable $\delta^{13}C$ values (Kohn 2010).

The $\delta^{13}C$ profile for WCM 5 gradually drops by 0.8‰ between the central samples of the second and third molars and remains at a relatively high level. Rather than reflecting the seasonal variation of vegetation in a single location, which might be expected to be more sinusoidal in shape (Balasse et al. 2009), it is possible that the $\delta^{13}C$ pattern observed in WCM 5 is indicative of vegetation gathered during the summer being fed to the animal during the winter, as discussed for Early Neolithic sheep (Balasse et al. 2013) and modern cattle (Towers et al. 2017). The difference in $^{87}Sr/^{86}Sr$ values between the second and third molar enamel samples of WCM 5 (Figure 4) may also reflect hay being brought to the animal from a different, though not necessarily distant, location. The difference in $^{87}Sr/^{86}Sr$ (0.00053) is less than the range observed in a single modern herd of grazing cattle (Towers et al. 2017). The climate during the Romano-British period was slightly warmer and drier than present times, and summer droughts might have been widespread during the 3rd – early 4th century AD (Müldner 2013). Thus, there is a likelihood that the climate would have affected the intra-tooth variability of the $\delta^{13}C$ values of the cattle in this study.

An interesting comparison may be made between third molar enamel $\delta^{13}C$ values for the Worcester cattle and equivalent values for cattle from Mid-Late Bronze Age Grimes Graves, Norfolk (Towers et al. 2017) and the Early Bronze Age barrows of Irthlingborough, Northamptonshire, and Gayhurst, Buckinghamshire (Towers et al. 2011). The Worcester values (between -13.3 and -11.9‰) are similar to those for Grimes Graves (between -13.5 and -11.3‰) but show little or no overlap with the values for Irthlingborough (between-15.3 and -13.4‰) and Gayhurst (between -15.1 and -13.1‰). Shifts in bone collagen $\delta^{13}C$ values have also been observed between Late Neolithic and Late Bronze Age humans from the Thames Valley in Buckinghamshire (Stevens et al. 2012) and between Beaker and Middle Iron Age humans from England and Eastern Scotland (Jay et al. 2012); in both cases $\delta^{13}C$ values from the earlier periods were lower. It has been suggested that these differences may indicate the combined effect of deforestation and a change in animal husbandry and/or foddering between the Early and Mid-Late Bronze Age periods rather than a change in climate (Jay et al. 2012). The cattle results from Worcester are aligned with this trend. Further interpretation is limited due to only having one reasonably complete profile (WCM 5) and a lack of comparative cattle data for Roman Britain.

6. Conclusion

The isotopic data provide strong evidence that none of the studied cattle were born and raised in close proximity to Worcester during the first c. 30 months of life based on the currently available and limited biosphere data. The cattle appear to have originated from more than one herd or place of origin, and the closest places of likely origins are the Old Red Sandstone of Herefordshire for WCM 4 and WCM 6 and regions of ancient rocks to the west in Wales for the remaining four. Alternative places further afield are northern Scotland, the Lake District or overseas in Ireland and mainland Europe.

Due to the advanced age of some of the cattle, severe tooth wear prevented seasonal profiles of diet and climate being constructed but one individual appears from the oxygen isotope data to have experienced or occupied a different climate to the other cattle during the first c. 30 months of life.

Finally, there is clearly a lack of stable isotope analysis conducted to study cattle during the Romano-British period, and this needs to be addressed before we can fully understand the implications of cattle husbandry and trade during the Roman period. Nonetheless, the multi-isotope approach has shed light on the possibility of Worcester as a regional cattle market during the Roman period, as we are able to speculate that cattle from different herds were moved into the region. It is hoped that the results from this study can serve as a reference for future studies.

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Figure and Table captions

Figure 1. Location of Worcestershire within the UK (top left) with Worcester highlighted (top right). Ordnance Survey map showing the location of The Hive excavation areas in Worcester (bottom). Publishing licence has been obtained from Ordnance Survey to reproduce the map.

Figure 2. Simplified geological map of the United Kingdom showing the location of Worcester.

Figure 3. Enamel sampling of the third molar of WCM 5. Ten intra-tooth powdered samples were obtained from the lingual surface of mesial lobe for $\delta^{18}O$ and $\delta^{13}C$ analyses, while a single chip of enamel was obtained from the lingual surface of mesial lobe for $^{87}Sr/^{86}Sr$ analysis.

Figure 4. $^{87}Sr/^{86}Sr$ values for the Worcester cattle. The 2σ error is contained within the symbols. The range of biosphere $^{87}Sr/^{86}Sr$ values expected for Worcester and its environs is that given by Evans et al. (2010) for areas of Triassic geology and Quaternary alluvium and river terrace deposits. Arrows show the sequence of molar formation and hence how the $^{87}Sr/^{86}Sr$ values change from the first months of life up to c. 30 months of age.

Figure 5. Intra-tooth $\delta^{18}O$ values for the Worcester cattle. Analytical precision was ±0.2‰ (1σ).

Figure 6. Intra-tooth $\delta^{13}C$ values for the Worcester cattle. Analytical precision was ±0.2‰ (1σ).

Table 1. Chronology of development for mandibular cattle molars (Brown et al. 1960). Timings relate to enamel matrix progression.

Table 2. Context information for each cattle mandible analysed in this study. Site period 4 = Roman (mid-2nd to early 3rd century AD); site period 5 = Roman (early/mid-3rd to early 4th century AD).

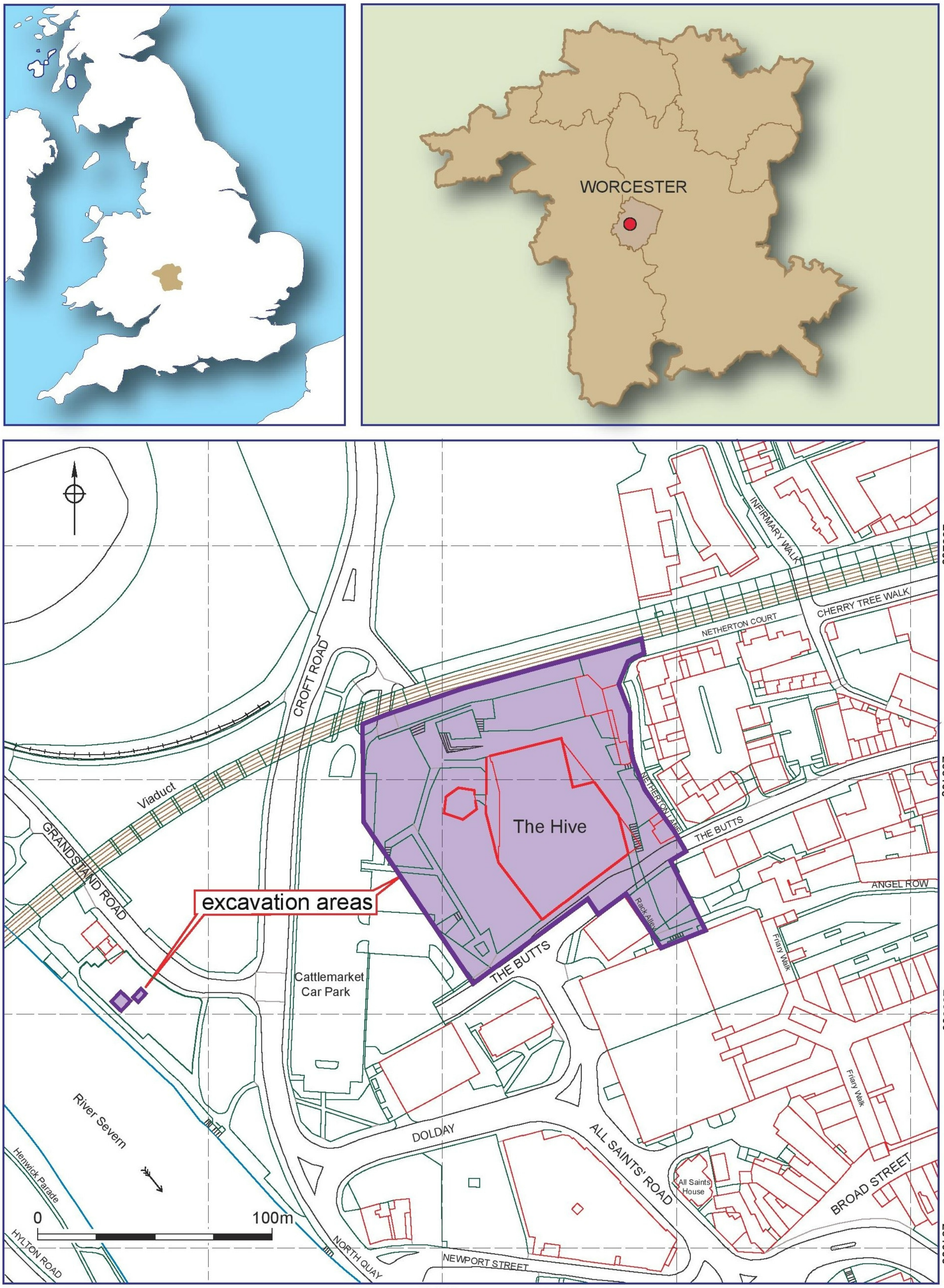
Table 3. Minimum values, maximum values and medians of $\delta^{18}O$ and $\delta^{13}C$ values for the enamel carbonate samples. A total of 41 carbonate samples have been obtained across the 6 cattle individuals in this study (refer Table S2 for full list of sample number for each individual).

Table 4. Published cattle enamel $^{87}Sr/^{86}Sr$ values.

Supplementary material

Table S1. $^{87}Sr/^{86}Sr$ values for first, second and third molars of each animal. Age of death was estimated following O'Connor (2003), which is based on the tooth wear stage (TWS) by Grant (1982).

Table S2. $\delta^{18}O$ and $\delta^{13}C$ values for all cattle enamel carbonate samples. WCM = excavation code; first digit = animal number; second digit = molar number; and third digit = position on tooth lobe (occlusal sample = sample 1).


WORCESTER
excavation areas
The Hive
Viaduct
GRANDSTAND ROAD
CROFT ROAD
NETHERTON COURT
CHERRY TREE WALK
INFIRMARY WALK
NETHERTON LANE
THE BUTTS
ANGEL ROW
Pack Alley
Friary Walk
Cattlemarket
Car Park
River Severn
Henwick Parade
HYLTON ROAD
DOLDAY
ALL SAINTS' ROAD
All Saints
House
BROAD STREET
NORTH QUAY
NEWPORT STREET
0
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255100
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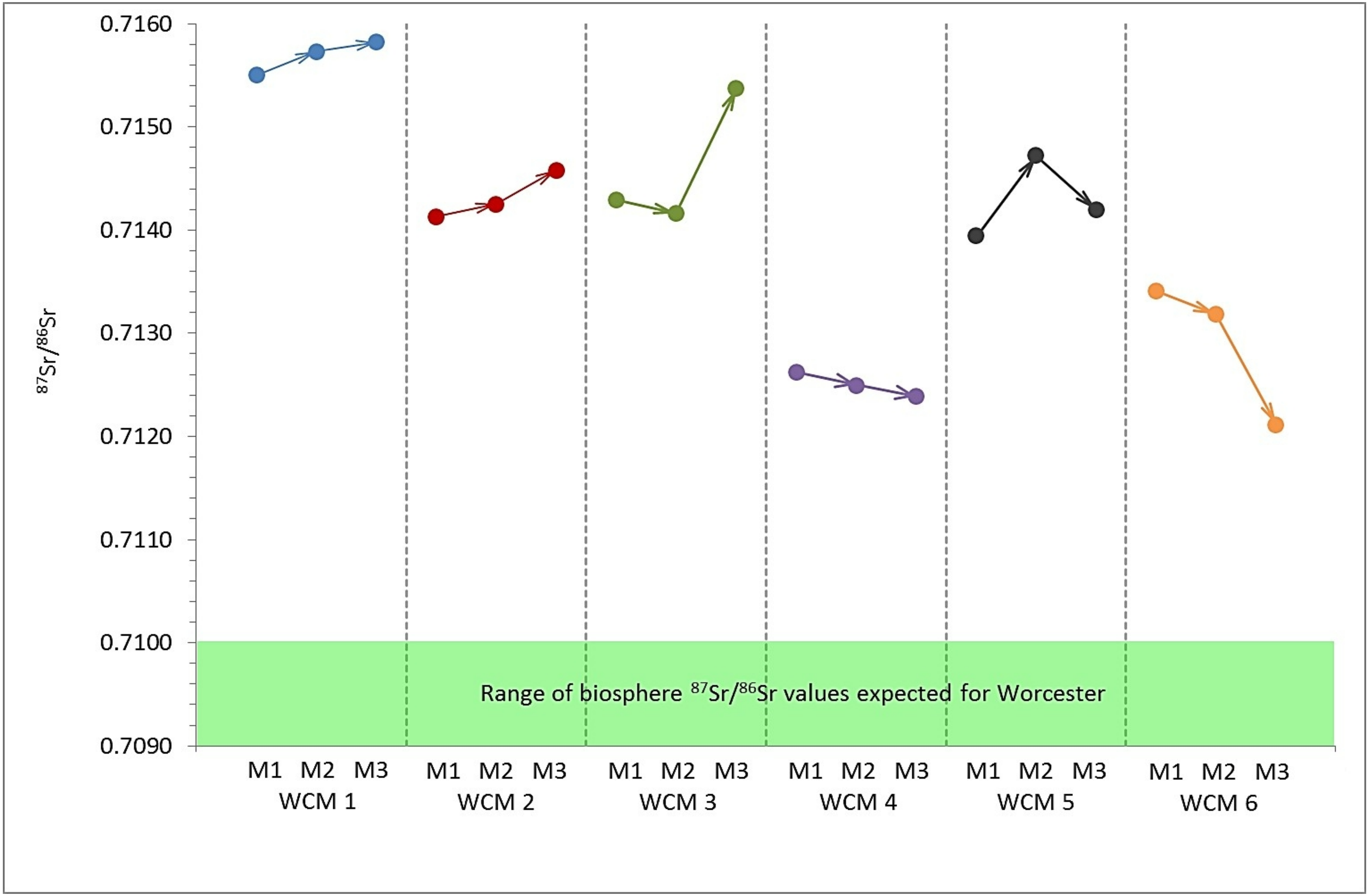
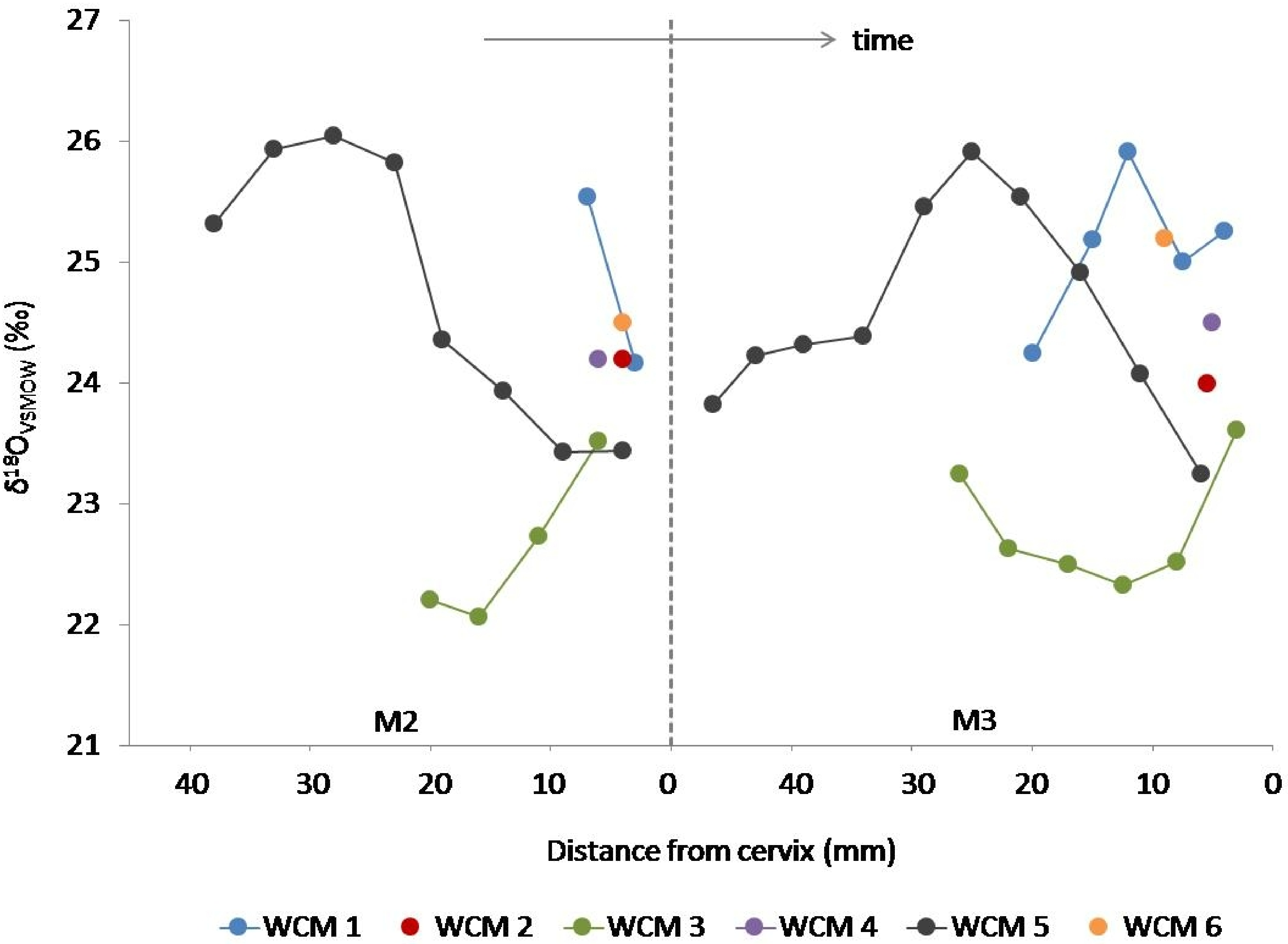
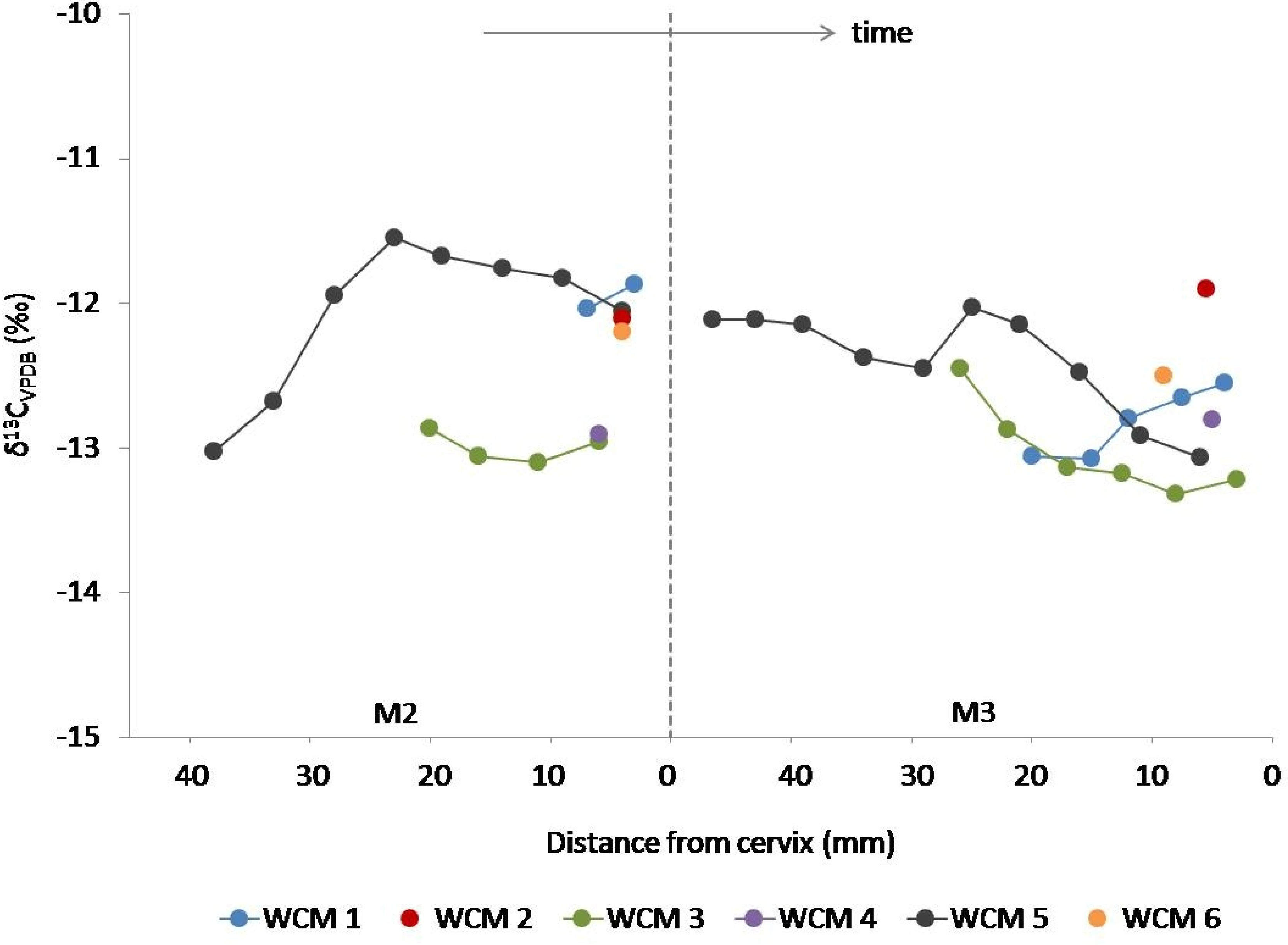
254900
384500
384600
384700
384800



0.7160
0.7150
0.7140
0.7130
0.7120
0.7110
0.7100
0.7090
87Sr/86Sr
Range of biosphere 87Sr/86Sr values expected for Worcester
M1 M2 M3
WCM 1
M1 M2 M3
WCM 2
M1 M2 M3
WCM 3
M1 M2 M3
WCM 4
M1 M2 M3
WCM 5
M1 M2 M3
WCM 6



27
26
25
24
23
22
21
time
$\delta^{18}O_{VSMOW}$ (‰)
M2
M3
40
30
20
10
0
40
30
20
10
0
Distance from cervix (mm)
WCM 1
WCM 2
WCM 3
WCM 4
WCM 5
WCM 6


-10
-11
-12
-13
-14
-15
$\delta^{13}C_{VPDB}$ (‰)
time
M2
M3
40 30 20 10 0 40 30 20 10 0
Distance from cervix (mm)
WCM 1
WCM 2
WCM 3
WCM 4
WCM 5
WCM 6

Supplementary References

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